OR/15/026 Metamorphism

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Regional setting

Dalradian sedimentary and volcanic rocks in north-east Scotland underwent regional and contact metamorphism during the Ordovician Grampian Orogeny. The Huntly and Turriff districts includes a major part of the type area for the 'Buchan' metamorphic facies series, characterised by low to intermediate pressures and relatively high temperatures (Read, 1952[1]; Stephenson and Gould, 1995[2]). It also includes the 'transition' to the Barrovian facies series in its western part. The regional metamorphic pattern is disrupted or strongly modified both by the Portsoy Shear Zone and by the presence of the various mafic-ultramafic plutons, notably Insch, Huntly and Knock (Figure 11). Peak metamorphic conditions were attained approximately coeval with emplacement of these plutons, which is dated at about 472 Ma ago, based on U-Pb zircon ages (Dempster et al., 2002[3]; Condon and Martin, cited in Oliver et al., 2008[4] as a personal communication, Carty et al., 2012[5]).

The Buchan facies series is defined by the successive appearance in pelitic rocks of biotite, cordierite, andalusite and sillimanite with increasing grade (Spear, 1993)[6]. Metamorphic grade increases from lower greenschist facies (chlorite zone) in the Turriff area to middle amphibolite facies (andalusite- and sillimanite-bearing zones) in the extreme south-east part of the district. Locally, it reaches upper amphibolite facies (sillimanite–potash feldspar zone) within and adjacent to the Huntly and Knock Gabbro-peridotite plutons and the Portsoy Gabbro-serpentinite Intrusion-swarm. These intrusions lie within and immediately east of the Portsoy Shear Zone (PSZ) (Ashworth, 1975)[7]. Here there is a convergence of metamorphic grade between the regional and contact metamorphic events, particularly adjacent to the larger mafic-ultramafic plutons.

West of the PSZ, a higher pressure Barrovian metamorphic event is superimposed on the earlier Buchan metamorphic assemblage, and, farther west still, on an early Barrovian mineral assemblage, resulting in secondary garnet, staurolite and kyanite. In the western parts of the district, kyanite commonly occurs as pseudomorphs after andalusite in the more pelitic lithologies (Beddoe-Stephens, 1990[8]; Chinner, 1980[9]; Chinner and Heseltine, 1979[10]).

Regional metamorphic pattern

Temperature and pressure conditions of the regional metamorphism

On the Banffshire coast, regional metamorphic temperatures of less than 500°C are recorded from assemblages in the axial parts of the Turriff Syncline, reflecting their shallower crustal levels (Hudson, 1985)[11]. To the west, south and east of this area metamorphic assemblages show that temperatures increased systematically, as demonstrated by the trace of the andalusite isograd (Harte and Hudson, 1979[12]; Baker, 1985[13]). South of the Aberchirder Granite, temperatures reached about 530°C within the andalusite zone (Hudson, 1985)[11]. In the south-west of the district, temperatures locally exceeded 600°C in the Portsoy Shear Zone (Beddoe-Stephens, 1990)[8]. Hornfels assemblages lying marginal to the large mafic-ultramafic intrusions locally record temperatures

between 600°C and 950°C (Ashworth and Chinner, 1978[14]; Droop and Charnley, 1985[15]; Droop et al., 2003[16]). Droop and Charnley (1985)[15] estimated that emplacement of these synmetamorphic mafic-ultramafic intrusions occurred at crustal depths of between 15 to 18.5 km (P = 4-5 kb). The subsequent work of Droop et al. (2003)[16] confirmed this estimated emplacement depth at 16 ± 3 km (P = 4.5 kb).

Pressures increase outwards from the Turriff Syncline reaching a maximum of 4 to 4.5 kb immediately east of the PSZ. However, to the west of the PSZ, Beddoe-Stephens (1990[8], 1992[17]) documented a distinct later pressure increase of at least 2 kb. Garnet zoning profiles and metamorphic mineral equilibria in this area are consistent with the local replacement of andalusite by kyanite, and appear to be coeval with the S2 fabric. The sharp westward pressure increase has been attributed to west- or west-north-west-directed overthrusting across the PSZ during D2.

Features of the regional metamorphic pattern

Mineral assemblages characteristic of the lowest chlorite zone occur in a north–south tract immediately west of the Devonian Turriff outlier, extending as far south as Auchterless [NJ 69 39] (Figure 11). In the Glens of Foundland, small clots of biotite overgrow and replace primary chlorite in slaty pelitic rocks.

Chloritoid occurs in low-grade rocks in the Hill of Foudland Slate Member (Leslie, 1988)[18]. Although stable over a relatively wide P-T range in low grade rocks, the chloritoid-chlorite-muscovite assemblages found here are limited to pressures of less than 3 kb. In thin section, pressure shadows and tails at the ends of obliquely orientated chloritoid laths indicate that these porphyroblasts predate the S2 fabric. The appearance of chloritoid is a function of the bulk composition, only occurring in oxidised, relatively aluminous, iron-rich rocks with >20% Al2O3 and Fe3+ >> Fe2+.

Chlorite-zone rocks are succeeded successively by biotite-, cordierite- and andalusite-zone rocks to the east, south and west. The transition from biotite-zone rocks, via the cordierite-zone, into andalusite-zone rocks can be seen in the Fyvie Gorge section, between Ardlogie [NJ 7804 3725] and the Ords [NJ 7890 3658], and in Clashindarroch Forest in the south-west of the District. In the Fyvie Gorge, chlorite- and biotite-bearing pelitic rocks become progressively more spotted until they take on a ‘knotted’ appearance as the cordierite and andalusite porphyroblasts grow in size and abundance. The porphyroblasts are wrapped by the S2 cleavage. In Clashindarroch Forest, the rocks are less schistose as those in the Fyvie Gorge and cordierite and andalusite are less-well developed, imparting a spotted, rather than strongly porphyroblastic appearance.

Higher grade rocks occur in Strathbogie to the north-west of the Ness Bogie, between Bridgend [NJ 5160 3580] and Bucharn [NJ 5210 3691]. They are characterised by andalusite-bearing schistose pelites and garnet-biotite-hornblende-plagioclase-bearing calc-silicate rocks. Good examples of the andalusite-bearing pelites are also exposed in the Burn of Auchintoul section by Kinnairdy Castle [NJ 609 498]. Evidence of transition from Buchan to Barrovian P-T conditions was recorded by Read (1923)[19], who noted that the andalusites are well formed, and that scarce staurolite and small garnets are also present here. The grey subhedral andalusite porphyroblasts contain abundant inclusions of quartz, biotite and minor graphite or magnetite. Droop et al. (2003)[16] carried out a detailed mineralogical study of the rocks within and adjacent to the Huntly Gabbro-peridotite Pluton. In schistose pelites from Clashmach Hill [NJ 498 385] they reported the assemblage muscovite-biotite-quartz-plagioclase±andalusite±staurolite±garnet±ilmenite. The andalusite forms subrectangular poikiloblasts up to 6 mm long with quartz inclusions, and staurolite forms micropoikiloblasts up to 3 mm long. In contrast the garnets are rare, tiny (about 150 µm diameter) and subhedral. Droop et al. (2003)[16] used version 2.75 of THERMOCALC (Holland and Powell,

1998)[20] to obtain P-T values of 2.7 ± 1.2 kb and 537 ± 42°C respectively, from the Clashmach pelites, values consistent with those obtained by Hudson (1985) from andalusite-zone rocks on the Banffshire coast.

Metamorphic assemblages within and adjacent to the Portsoy Shear Zone generally lie in the lower to middle amphibolite facies. Beddoe Stephens (1990)[8] used several reaction-based geothermometers and geobarometers, and garnet zoning patterns, to define P-T values in three Argyll Group pelite samples from the western side of the Huntly Pluton that lie within the Portsoy Shear Zone. Calculated P-T values ranged between 4 kb and 4.5 kb and between 580°C and 610°C, respectively. Droop et al. (2003)[16] applied more sophisticated methods (see above) to medium-grained plagioclase- and quartz-rich garnet-biotite gneisses containing minor staurolite and fibrolitic sillimanite. These are associated with finer-grained muscovite-bearing schistose garnet-biotite pelites and crop out by Cairnie at [NJ 482 446]. P-T values of 6.5 ± 1.3 kb and 637 ± 31°C were obtained from the finer-grained pelite. These Barrovian assemblages and P-T values are compatible with middle amphibolite-facies metamorphism.

To the west of the PSZ the metamorphic assemblages are of lower amphibolite grade. Pelitic units in the Mortlach Graphitic Schist and Fordyce Limestone formations contain kyanite, staurolite and garnet. Euhedral kyanite occurs in graphitic pelite in the Ardonald limestone quarries [NJ 4617 4434], and Read (1923)[19] recorded staurolite, kyanite and garnet from the Ardonald Burn section just to the north. Staurolite and andalusite (var. chiastolite) occur in abundant graphitic pelite float of the same unit immediately west of the district on the eastern slope of Cairds Hill around [NJ 4314 4648]; the andalusite is probably pseudomorphed by kyanite. Calc-silicate bearing lithologies in the Pitlurg Calcareous Flags Formation are dominated by tremolite and phlogopite; hornblende is present locally. The generally flaggy psammitic and minor semipelitic units of the Findlater Flag Formation contain no metamorphic index minerals.

Staurolite, kyanite and garnet are common in schistose pelites within the Fordyce Limestone Formation in the Paithnic–Grange–Edingight area, north of the River Isla. Notable exposures occur in the Burn of Paithnick [NJ 4811 5402], Burn of Braco [NJ 5088 5373]. Similar metamorphic assemblages are also found south of the River Isla, where the pelites crop out on the northmost flank of Balloch Hill [NJ 472 496] and in the Mill of Wood Burn.

In thin section, staurolites typically consist of a pale yellow pleochroic core with abundant inclusions that define an earlier fabric, surrounded by a deeper yellow pleochroic and inclusion-poor rim. Many garnet porphyroblasts show evidence for two or even three distinct growth phases, again with inclusion-rich cores and inclusion-poor rims; some show a distinct rim zone representing re-equilibration under later lower grade conditions. Kyanites are commonly lath-shaped and show varying degrees of alteration to white mica. In some examples they exhibit similar inclusion patterns to the staurolites.

The fabrics and mineralogy indicate that primary metamorphic mineral growth followed D1 deformation, with the second phase of growth coeval with D2 deformation. In the western part of the Huntly district, both events occurred under middle amphibolite facies conditions within the kyanite zone.

Hornfelsed and migmatitic rocks

Rocks associated with the Huntly and Knock plutons

Associated with the large mafic-ultramafic plutons and related intrusions are contaminated mafic

rocks, and migmatitic and xenolithic rocks that include numerous hornfelsed metasedimentary enclaves. Ashworth (1975[7], 1976[21]) ascribed these high grade rocks that lie within and immediately east of the Huntly, Knock and Portsoy intrusions, and the nearby migmatitic gneisses of the Cowhythe Psammite Formation, to the sillimanite-potash feldspar zone (upper amphibolite grade). Peak metamorphic temperatures estimated for these rocks range between 700° and 950°C, with pressures ranging from 4 to 5 kb (Ashworth and Chinner, 1978[14]; Droop and Charnley, 1985[15]; Droop et al., 2003[16]). Many of the rocks are migmatites and it can be difficult to separate migmatitic and partially melted metasedimentary rocks from contaminated mafic igneous rocks, both in the field and petrographically. Indeed, the distinction between hybrid igneous rocks and partially melted pelitic rocks may be gradational in some areas. The rocks are generally 'noritic' and contain upper-amphibolite facies mineral assemblages that typically include cordierite, hypersthene, sillimanite, garnet, biotite, K-feldspar and hercynite (spinel) (Read, 1923[19]; Ashworth, 1976[21]; Droop and Charnley, 1985[15]; Droop et al., 2003[16]; see also discussion of the Huntly and Knock plutons, Emplacement model to comparison with pretectonic mafic-ultramafic intrusions).

Droop et al. (2003)[16] also used THERMOCALC in combination with garnet-biotite, garnet-cordierite and garnet-orthopyroxene Fe, Mg exchange geothermometers, the orthopyroxene-garnet geothermometer, and the garnet-orthopyroxene-plagioclase-quartz geobarometer to obtain P-T values on both nonmigmatitic and migmatitic hornfelsed rocks that occur within and marginal to the Huntly pluton. A nonmigmatitic cordierite-sillimanite-bearing hornfelsed pelite, was sampled from a large loose block on the east side of the River Deveron, north of Dunbennan Hill at [NJ 499 422]. It contains scattered subhedral garnet porphyroblasts up to 3 mm across, and randomly orientated 'bundles' of prismatic sillimanite, typically about 8 x 2 x 2 mm, interpreted as pseudomorphs after andalusite. The porphyroblasts lie in a fine-grained granoblastic matrix of biotite, cordierite, plagioclase, quartz and ilmenite. The cordierites are locally replaced by chlorite + andalusite. P-T values calculated for this rock were 5.1 ± 0.8 kb and 628 ± 75°C respectively, taking an arbitrary aH_2O value of 1.0. Droop and Charnley (1985)[15] describe hybrid mineral assemblages from the western side of the Huntly intrusion at Cuttle Hill [NJ 494 474]; in thin section, sector-twinned cordierites, 0.5 to 1 cm across, are surrounded by staurolite and gedrite clusters, set in a matrix of biotite, plagioclase, cordierite and quartz with minor garnet and sillimanite.

The migmatitic rocks correspond mainly to the 'cordierite-bearing migmatites' of Ashworth (1976)[21]. They include stromatic metatexites that are abundant around Cumrie and Cormalet Hill [NJ 523 448] in the northern part of the Huntly Pluton. These hornfels rocks comprise blue-grey fine-grained cordierite-plagioclase-K-feldspar-ilmenite melanosomes with veins of granitic leucosomes, mostly < 1 cm thick, and commonly in subparallel arrays. The leucosomes are garnetiferous and make up some 20 to 40 per cent of the rock type. They also form branching, anastomosing and discordant veins indicating the presence of a melt phase. Droop et al. (2003)[16] also recognise garnet-bearing tonalites and cordierite-norites that they term schollen diatexites. These rock types, which consist of about 70 to 95 per cent of mobilised igneous textured mobilised material, are common and form a significant component part of the Huntly and Knock plutons. Most of the schollen are pelitic but quartzite and calc-silicate rocks also occur. In the Cormalet–Cumrie area garnet-bearing tonalites contain euhedral inclusion-free garnets up to 1 cm across and sporadic blocky cordierites in a medium- to coarse-grained matrix of biotite, quartz and euhedral plagioclase. Small patches of fibrolite were also recorded. The orthopyroxene-bearing varieties, termed cordierite norites by Read (1923)[19], and 'noritoids' by Ashworth (1976)[21] crop out at Battlehill Quarry [NJ 539 395], in the River Deveron at Castle Bridge [NJ 533 409] and north of Dunbennan Hill at [NJ 499 422]. Droop et al. (2003)[16] noted that at Battlehill Quarry the cordierite norites have a mafic igneous appearance and form discordant bodies with sharp contacts against gabbros and high-grade hornfels. The rocks are medium-grained and consist essentially of randomly orientated cordierite, orthopyroxene, garnet and plagioclase. The cordierites are fresh and form subhedral prisms with simple or sector twinning

and the orthopyroxenes are markedly pleochroic and form elongated subhedral prisms with rounded plagioclase inclusions. Garnets are generally less abundant than cordierite and orthopyroxene; they form subhedral grains that are either inclusion-free or contain scattered ilmenite and biotite inclusions. Plagioclase crystals show marked normal zoning with An-rich cores (labradorite to bytownite) and upper andesine rims. In parts they also exhibit oscillatory zoning. Biotites form thick books up to 1.5 mm across in the Castle Bridge samples, but are mainly interstitial in other examples. Quartz is present in only minor amounts, commonly as small cuspate interstitial grains. K feldspar is also only rarely present, mainly as interstitial microperthite. Dark green hercynite is a more abundant component. In the Battlehill samples it is a minor phase, mostly forming inclusions within cordierite, but it is modally abundant in samples from Castle Bridge and Dunbennan Hill where it forms oblong clusters up to 5 x 2 x 2 mm of 0.01 to 1 mm granules intergrown with fine-grained cordierite. The clusters have square cross-sections and Droop et al. (2003)[16] recorded that they are locally cored by aggregates of prismatic sillimanite, indicating that they are pseudomorphs after that mineral. Retrograde textures include biotite-quartz intergrowths replacing orthopyroxene and fine-grained biotite rims on garnets. Droop et al. (2003)[16] interpret the mineralogy and texture of these diatexites as indicating the presence of a significant melt phase and hence that the cordierite norites represent cumulates. They favour a process of partial melting with the main mineralogy generated as solid products of incongruent melting reactions.

Droop et al. (2003)[16] also recognised orthopyroxene-cordierite-bearing pelitic hornfels that form schollen and xenoliths within the cordierite norites and occur as screens and xenoliths in the gabbros in the southern and western parts of the Huntly Pluton. These are dark blue-grey, fine-grained, cordierite-rich rocks commonly containing small (1 to 2 mm) garnet porphyroblasts. Their matrices typically consist of small equant grains of orthopyroxene, plagioclase and twinned cordierite, with abundant granules of ilmenite and, in many samples, of hercynite. In some examples cordierite makes up >60 per cent of the mode. Quartz and K-feldspar are normally absent, and biotite rare to absent, except in some of the more leucocratic layers, which possibly represent leucosomes.

Examples of high-grade hornfelsed rocks are also found within and adjacent to the Knock Pluton. About 1 km south of Knock Hill summit at [NJ 537 542] cordierite and sillimanite occur in a plagioclase (andesine)-hypersthene-biotite-magnetite rock. Garnets are common in these rocks, particularly in the hybrid basic-metasedimentary rocks, where locally they attain several centimetres in diameter, e.g. on the west flank of Barry Hill [NJ 558 545], and on Wether Hill [NJ 567 542].

Cores from the Drumnagorrach and Claymires boreholes (drilled adjacent to the western and eastern margins of the Knock intrusion respectively) contain hornfelsed, amphibolite grade, semipelitic and calcareous metasedimentary rocks interlayered with foliated metabasic rocks. The calc-silicate rocks contain large pods of diopside, and in the semipelites biotite-magnetite-?cordierite and garnet-biotite-sillimanite assemblages are present.

Droop et al. (2003)[16] obtained a range of P-T values for the cordierite norites and high-grade hornfelses related to the Huntly Pluton based on the various geothermometers and geobarometers and THERMOCALC. Best-fit results gave pressures in the range 4 to 5 kb and temperatures between 900 and 950°C with aH_20 values being constrained to lie between 0.1 and 0.4. They also used the whole-rock chemistry of 72 metasedimentary and mafic igneous rocks to show that the orthopyroxene-cordierite hornfelses and the cordierite norites were relatively depleted in 'granitophile' components compared to their probable pelitic protoliths. The hornfelses and migmatites showed chemistries compatible with being restites. Mass balance calculations and modelling suggested that the amount of melt produced and subsequently migrated from the hornfelses and cordierite norites was about 57 per cent and 53 per cent respectively. If the fugitive

melts were granitoid (72–75% SiO_2), as seems likely on petrographical grounds, they argued that, as most of the orthopyroxene-cordierite hornfelses were completely drained of melt during their formation, the degree of partial melting attained about 60 per cent. Droop et al. (2003)[16] also carried partial melt experiments using two samples of schistose pelite (Clashindarroch Formation) from Clashmach Hill [NJ 498 385], one containing andalusite and minor garnet and the other being free of these minerals. The rock powders were heated to 900°C for 150 hours under a pressure of 5 kb, with log*f*H2 set at -1 and an aH_2O of 0.35. The resulting melt was quenched and studied under an SEM. The assemblage obtained from the andalusite-bearing pelite consisted of orthopyroxene, cordierite, hercynite, ilmenite and minor biotite in a matrix of glass. The pelitic sample lacking andalusite produced cordierite, hercynite and ilmenite in the glass matrix. Melt proportions were about 60 and 65 per cent respectively and melt compositions were reasonably uniform and corresponded to peraluminous potassic granite. Similar results have been obtained by other authors from pelitic systems (Carrington and Harley, 1995[22]; Stevens, 1995[23]). Droop et al. (2003)[16] suggest that the granitoid melts underwent little or no in situ fractional crystallisation and contributed to the Early Ordovician peraluminous two-mica granites that are characteristic of north-east Scotland. These intrusions range in size from small pods or dykes up to large plutons (e.g. Strichen, Aberchirder). They show isotopic signatures implying an upper crustal source and similar emplacement ages (about 470 Ma) to the mafic-ultramafic intrusions. They also noted that the prograde P-T path of the contact metamorphosed rocks in the south-west part of the Huntly Pluton had a low positive dP/dT slope, implying an increased lithostatic load at the time of gabbro intrusion. They suggested that the gabbro itself may have been responsible for this increased load.

Other contact metamorphic rocks

Rocks in the Macduff Slate Formation are contact-metamorphosed along the northern margin of the Insch Intrusion (Leslie, 1988[18]). The aureole north of the Boganclogh Sector, is well seen on the northern flanks of Hill of Noth [NJ 4984 3008] and on the watershed between Glen of Noth and Kirkney Water. It contains progressively more spotted pelitic rocks which become tough, fine-grained, cordierite and andalusite hornfelses immediately adjacent to the intrusion. The incoming of cordierite-hornfelses takes place generally over a few tens of metres. Although pelites in the Macduff Slate Formation are spotted over a wide area north of the cordierite-hornfelses, much of this is probably due to the regional metamorphism. However, a 500 m-wide spotted zone extending from south of Quarry Hill [NJ 4673 3173], eastwards into Glen of Noth is part of the contact aureole of the Insch intrusion. The limit of cordierite-hornfelses runs approximately south-east across the summit ridge of Hill of Noth. The lower half of the east ridge of Hill of Noth is comprised of very dark grey, indurated gritty arenites.

In thin section, the regional chlorite+quartz-dominated matrix in the hornfelses is seen to have recrystallised to fine-grained more equant biotite and quartz in psammitic and semipelitic units. A well developed, but faint, penetrative fabric is present in the groundmass of hornfelses, clearly wrapping porphyroblasts, but overgrown by late chlorite. This is probably the regional, S2 fabric that forms the second cleavage immediately outwith the aureole (Fettes, 1970[24]). Where developed, porphyroblasts of cordierite and andalusite occur in a very fine-grained groundmass consisting largely of sericite with abundant olive brown clots of biotite and large grains of magnetite. The cordierite porphyroblasts are rounded with diffuse margins. Abundant inclusions preserve an S1 internal fabric at a high angle to the groundmass fabric. Cordierite rims are generally altered to yellow pinite, particularly adjacent to late chlorite porphyroblasts. Andalusite (var. chiastolite) forms rectangular laths, or square to rhomboid sections. Inclusions are common. In some sections the andalusite is still fresh, but generally it has been altered to white mica aggregates.

As described above, the most extreme hornfelsing occurs in metasedimentary enclaves within and

adjacent to the Huntly–Knock intrusion. These hornfelses include sillimanite, spinel and corundum in addition to andalusite and cordierite. In places, temperatures have been sufficiently high (c. 900°C) for sedimentary lithologies to be assimilated into the basic magmas, giving rise to hybrid rocks which contain highly aluminous phases together with igneous minerals (Read, 1923[19]; Ashworth and Chinner, 1978[14]; Droop and Charnley, 1985[15]; Droop et al., 2003[16]).

Hornfelses are developed in gritty arenites and slaty pelites of the Macduff Slate Formation adjacent to the eastern margin of the Aberchirder Granite. The transition from pelites into the hornfelses occurs around Skeibhill [NJ 635 522], about 400 m east of the granite contact (Read, 1923)[19]. Massive 'speckled grey hornfels' from a quarry 460 m east of Quarryhill at [NJ 6332 5152] contains colourless to pink, clear, andalusite prisms with sparse inclusions in a fine-grained granular matrix of quartz, muscovite, biotite, iron oxides and minor cordierite (Read, 1923)[19]. The marginal veined contact zone at the south-east edge of Cleanhill Wood is described in the section on the Aberchirder Granite.

Retrograde metamorphism

The whole district has been subject to a late retrogressive metamorphic event of variable intensity. It is characterised by new chlorite growth and less commonly, white mica. New chlorite porphyroblasts several millimetres across overgrow existing fabrics, particularly in semipelite and micaceous psammite lithologies. Chlorite partly replaces earlier ferromagnesian minerals in the more pelitic rocks; in calc-silicate assemblages, it commonly replaces hornblende. Large, late-stage chlorite porphyroblasts form prominent green spots in micaceous psammites in the Den of Pitlurg at [NJ 4497 4534]. Cordierite is altered to pinite, andalusite is replaced by muscovite sheaves and sericite, and plagioclase is partly altered to sericite.

Retrograde metamorphic effects occur in the PSZ (see above) and in individual shear zones in the basic intrusions. Kyanite shows marginal alteration to white mica aggregates. Although the retrogression is the last regional metamorphic event in the district, late chlorite is commonly kinked, indicating localised later deformation or movements.

References

1. ↑ READ, H H. 1952. Metamorphism and migmatisation in the Ythan Valley, Aberdeenshire. *Transactions of the Geological Society of Edinburgh*, Vol. 15, 265–279.
2. ↑ STEPHENSON, D, and GOULD, D. 1995. The Grampian Highlands: British Regional Geology. (Keyworth, Nottingham: British Geological Survey.) ISBN 0 11 884521 7
3. ↑ DEMPSTER, T J, ROGERS, G, TANNER, P W G, BLUCK, B J, MUIR, R J, REDWOOD, S D, IRELAND, T R, and PATERSON, B A. 2002. Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints from U-Pb zircon ages. *Journal of the Geological Society of London*, Vol. 159, 83–94.
4. ↑ OLIVER, G J H, WILDE, S A, and WAN, Y. 2008. Geochronology and geodynamics of Scottish granitoids from the late Neo-proterozoic break-up of Rodinia to Palaeozoic collision. *Journal of the Geological Society of London*, Vol. 165, 661–674.
5. ↑ CARTY, J P, CONNELLY, J N, HUDSON, N F C, and GALE, J F W. 2012. Constraints on the timing of deformation, magmatism and metamorphism in the Dalradian of NE Scotland. *Scottish Journal of Geology,* Vol. 48, 103–117.
6. ↑ SPEAR, F S. 1993. *Metamorphic phase equilibria and pressure-temperature-time paths*. Mineralogical Society of America Monograph Series.
7. ↑ [7.0] [7.1] ASHWORTH, J R. 1975. The sillimanite zones of the Huntly–Portsoy area in the north-

east Dalradian, Scotland. *Geological Magazine*, Vol. 112, 113–136.
8. ↑ 8.0 8.1 8.2 8.3 BEDDOE-STEPHENS, B. 1990. Pressures and temperatures of Dalradian metamorphism and the andalusite-kyanite transformation in the north-east Grampians. *Scottish Journal of Geology*, Vol. 26, 3–14.
9. ↑ CHINNER, G A. 1980. Kyanite isograds of Grampian metamorphism. *Journal of the Geological Society of London*, Vol. 137, 35–39.
10. ↑ CHINNER, G A, and HESELTINE, F J. 1979. The Grampide andalusite/kyanite isograd. *Scottish Journal of Geology*, Vol. 15, 117–127.
11. ↑ 11.0 11.1 HUDSON, N F C. 1985. Conditions of Dalradian metamorphism in the Buchan area, NE Scotland. *Journal of the Geological Society of London*, Vol. 142, 63–76.
12. ↑ HARTE, B, and HUDSON, N F C. 1979. Pelite facies series and the temperatures and pressures of Dalradian metamorphism in E Scotland. 323–337 in The Caledonides of the British Isles – reviewed. HARRIS, A L, HOLLAND, C H, and LEAKE, B E (editors). *Special Publication of the Geological Society of London*, No. 8.
13. ↑ BAKER, A J. 1985. Pressures and temperatures of metamorphism in the eastern Dalradian. *Journal of the Geological Society of London*, Vol. 142, 137–148.
14. ↑ 14.0 14.1 14.2 ASHWORTH J R, and CHINNER, G A. 1978. Coexisting garnet and cordierite in migmatites from the Scottish Caledonides. *Contributions to Mineralogy and Petrology*, Vol. 65, 379–394
15. ↑ 15.0 15.1 15.2 15.3 15.4 15.5 DROOP, G T R, and CHARNLEY, N. 1985. Comparative geobarometry of pelitic hornfelses associated with the newer gabbros: a preliminary study. *Journal of the Geological Society of London*, Vol. 142, 53–62.
16. ↑ 16.00 16.01 16.02 16.03 16.04 16.05 16.06 16.07 16.08 16.09 16.10 16.11 16.12 16.13 16.14 16.15 16.16 DROOP, G T R, CLEMENS, J D, and DALRYMPLE, D J. 2003. Processes and conditions during contact anatexis, melt escape and restite formation: the Huntly Gabbro Complex, NE Scotland. *Journal of Petrology*, Vol. 44, 995–1029.
17. ↑ BEDDOE-STEPHENS, B. 1992. Pressure and temperatures of Dalradian metamorphism, Keith–Sandend area, North-east Grampians. *British Geological Survey Technical Report*, WG/92/98.
18. ↑ 18.0 18.1 LESLIE, A G. 1988. A chloritoid-bearing paragenesis in the Macduff Slates of Central Buchan. *Scottish Journal of Geology*, Vol. 24, 223–231.
19. ↑ 19.0 19.1 19.2 19.3 19.4 19.5 19.6 READ, H H. 1923. *The geology of the country around Banff, Huntly and Turriff (Lower Banffshire and North-west Aberdeenshire) Explanation of Sheets 86 and 96*. Memoir of the Geological Survey, Scotland. (Edinburgh: HMSO).
20. ↑ HOLLAND, T J B, and POWELL, R. 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*, Vol. 16, 309–343.
21. ↑ 21.0 21.1 21.2 21.3 ASHWORTH, J R. 1976. Petrogenesis of migmatites in the Huntly – Portsoy area, north-east Scotland. *Mineralogical Magazine*, Vol. 40, 661–682.
22. ↑ CARRINGTON, D P, and HARLEY, S L. 1995. Partial melting and phase relations in high-grade metapelites — an experimental petrogenetic grid in the KFMASH system. *Contributions to Mineralogy and Petrology*, Vol. 120, 270–291.
23. ↑ STEVENS, G. 1995. Compositional controls on partial melting in high-grade metapelites: a petrological and experimental study. Unpublished PhD thesis, University of Manchester.
24. ↑ FETTES, D J. 1970. The structural and metamorphic state of the Dalradian rocks and their bearing on the age of emplacement of the basic sheet. *Scottish Journal of Geology*, Vol. 6, 108–118.

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